Safe Injection into the LHC

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Abstract

The LHC injection process comprises extraction from the SPS, transfer through the transfer lines TI 2 and TI 8 and finally injection into the LHC in IR2 and IR8. The nominal intensities foreseen for injection are over an order of magnitude above the damage limit. Equipment failures resulting in beam loss will therefore cause severe damage to the SPS, the transfer lines or the LHC. Effective active (interlock) and passive (collimator) machine protection is therefore essential. The consequences of various failures such as kicker erratics, power converter faults, etc. have been investigated for beam 2 with particle tracking. A full aperture model of the transfer line and injection region was taken into account. The requirements for active protection by surveillance of key equipment and passive protection (TCDI, TDI-TCLI) are presented. Consequences for the commissioning phase of the LHC are discussed in the context of the likely LHC commissioning strategy.

INTRODUCTION

The energy stored in the injected 450 GeV beam is 2.3 MJ. The assumed damage limit for energy deposition in equipment is 100 J/cc. In terms of losses the damage limit corresponds to $\sim 2.4 \cdot 10^{12}$ protons, which is about 5% of an ultimate injected batch.

The aperture in the transfer line is very tight; at many locations it is smaller than 7 σ. The available aperture in the LHC at 450 GeV is assumed to be 7.5 σ.

Failures like magnet trips, kicker erratics, timing errors, operator errors, etc. can move the trajectory far outside the available aperture; some failures change the trajectory drastically in a very short time. During a power converter fault of the MSE, the extraction septa in the SPS, the trajectory is moved by 40 σ in 1 ms.

The different failures are divided into three classes. We speak of *slow failures*, if the trajectory is changed by 10σ within more than 2-3ms. If the trajectory is changed by this amount within less than 2-3ms, this failure is called *fast failure*. Kicker erratics etc., which change the trajectory by this amount in μs, are called *ultra-fast failures*.

MACHINE PROTECTION STRATEGY

The most effective strategy for protecting the machine components is avoiding dangerous situations. Thus different procedures and concepts are worked out to minimise the risk probability for failures. An example is the "beam presence" condition. It will be explained below.

In the case of failures, protection systems must be in place. For slow failures surveillance plus interlocking to inhibit the injection/extraction guarantees sufficient protection (active protection). Fast and ultra-fast failures can only be covered by passive protection like collimators and absorbers. These passive protection devices must be robust enough to withstand a full injected batch. They are therefore made of low-Z materials (C, hBN).

Beam Presence Condition

Injection of high intensity beam (intensity above the damage limit) into the LHC is only possible if there is already beam circulating in the LHC. This is the "beam presence" condition which protects the LHC against many possible causes for fast beam loss during injection like wrong settings, LHC magnet trips, etc., [1].

The beam presence flag is based on reliable monitoring of the SPS and LHC intensity and a hardwired interlock between the SPS and LHC intensity monitoring systems and the LHC injection Beam Interlock Controller (BIC).

INJECTION PROTECTION SYSTEMS

In the following the active and passive injection protection systems are described.

Active Protection - Interlock System

Fig. 1 summarises the hardwired interlocks involved in the injection process, [2]. The LHC BIC transmits the *injection permit* to the LHC injection kicker based on the SPS and LHC intensity and LHC energy from the SLP (safe LHC parameters). Injection is only possible if the LHC BIC has the *LHC beam permit* (status of LHC is OK). The injection hardware must be in the appropriate status, the TDI and the transfer line collimators must have correct settings, the LHC equipment must have injection settings, etc.

Extraction from the SPS is only possible if injection into the LHC is possible or if one the TEDs is in (complication for LSS4 where besides LHC extraction also CNGS extraction is possible). Thus the LHC BIC also distributes the injection permit to the SPS BIC. The extraction permit is transmitted to the SPS extraction kicker by the SPS BIC based on the SPS hardware status, transfer line status, fast beam losses in extraction region, etc. Important hardwired links to the SPS BIC concern the extraction, like the bumped beam position at the extraction bumpers, the current of the MSE, the girder position of the MSE and the status of the MKE, the extraction kicker.

The power converter surveillance system is a vital part of the interlock system. The present power converter surveillance (PCS) system has a reaction time of $\geq$3ms

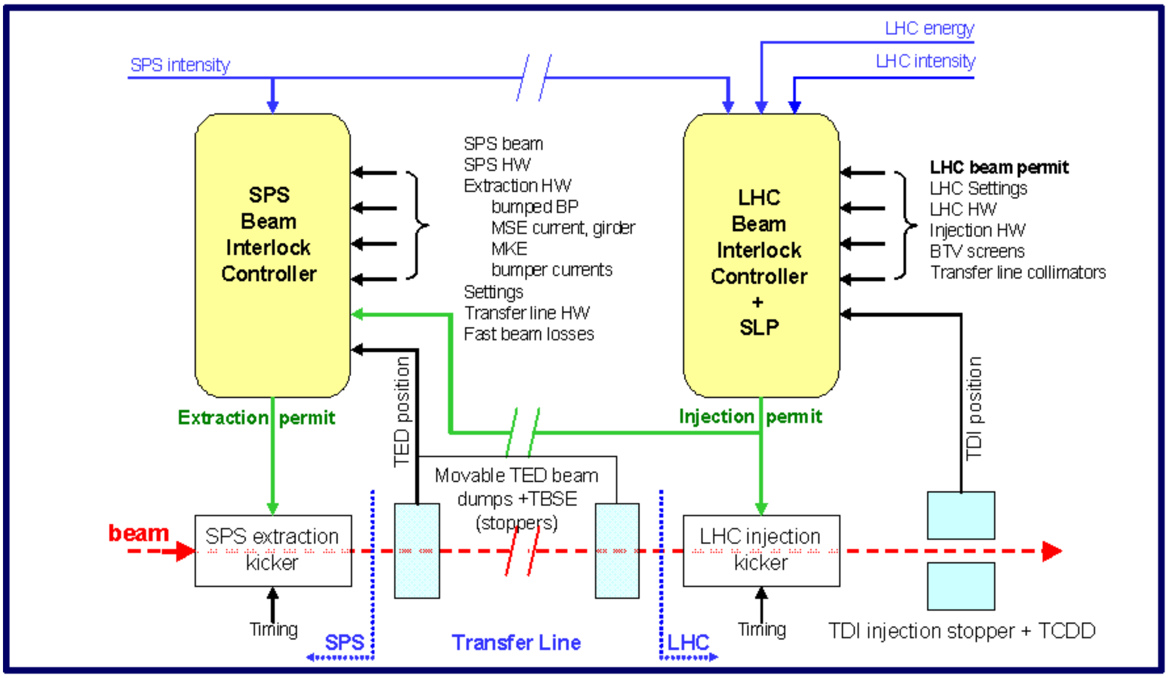

Figure 1: Overview of the hardwired interlock system for injection protection.

(ROCS software). A dedicated fast current decay monitoring (FCDM) system could have a reaction time of ∼1ms. This system is not in the present baseline, but has shown to be mandatory (see below).

In addition to hardwired interlocks, software interlocks are applied. They are much slower than hardware interlocks and not necessarily failsafe. They are thus used for less critical parameters (beam quality, trajectory in transfer lines,...) and for redundancy.

The software interlocking system is also used to cross-check reference values. In case of the PCS, the readings of the surveillance instruments are compared with local reference values in the local front-ends. Reference values are machine mode dependent (values plus tolerances depend on intensity, energy, type of beam, etc.). To avoid errors like checking the readings against a wrong set of reference values, the software interlock system compares the local reference values with central reference values.

Passive Protection - Collimators

Collimation systems can be divided into generic and dedicated collimation systems. Generic systems protect tight aperture against any failure upstream, dedicated collimation systems protect any aperture downstream against one particular failure.

The transfer line collimators, the TCDI, shadow the LHC aperture. The TCDI system is a generic passive protection system with full phase space coverage against any failure upstream of the collimation section. The 0°-collimator is also a local protection of the MSI against all upstream failures.

For kicker failures dedicated collimators are foreseen. The TDI (injection stopper) and the TCLI protect the LHC against injection kicker (MKI) failures. The TPSG shadows the MSE coil against extraction kicker (MKE) failures in the SPS.

The septum magnets at injection (MSI) and extraction (MSE) do not have any dedicated passive protection devices downstream. Protection against MSE or MSI failures relies solely on power converter surveillance and interlocking.

TCDI – Transfer Line Collimation

As mentioned above, the main objective of the TCDI collimators is to protect the LHC and the MSI which are difficult to replace and only a few spares are available, [3]. They are thus in the last 300m of the transfer lines, within the matching sections of the lines to the LHC. Their design is based on the TCS layout (secondary ring collimator) with 1.2 m C jaws, robust enough to withstand the impact of a full ultimate batch.

The TCDI system is a 3-phase collimation system with 3 collimators per plane. Between two subsequent collimators there are $180° \cdot n + 60°$ phase advance.

The elements downstream of each TCDI have to be equipped with a 50 cm Fe mask to be locally shielded against showers generated in the TCDIs in the case of beam loss. The necessity of local shielding was a result of a comprehensive FLUKA study of impact scenarios with the whole geometry of the last 300 m of TI 8 implemented in FLUKA.

The setting of the TCDI is 4.5σ with relatively large tolerances of 1.4 σ (knowledge of beam axis and beam size, mechanical tolerances, etc.). The protection level in terms of maximum possible amplitudes into the LHC was defined with a Monte-Carlo simulation including all imperfections like β-beating, mismatch from the SPS, tolerances, etc. The tight setting guarantees maximum amplitudes of 6.9 σ leaving the collimation section.

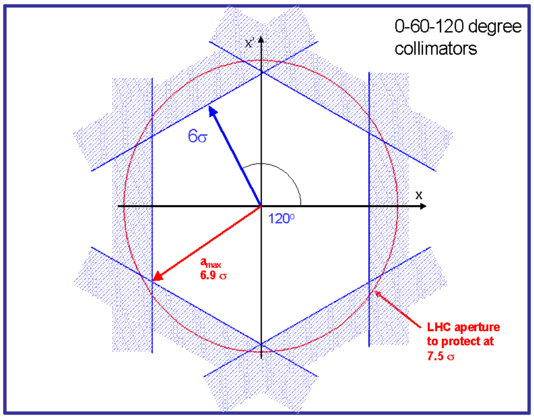

Figure 2: The phase-space coverage of a 3-phase collimation system.

TDI - TCDD - TCLI

The system TDI-TCDD-TCLI protects against MKI failures [4]. The 4 m long, TDI is located 90° downstream of the MKI and is made of hBN for robustness and protects against kicker failures on the injected as well as the circulating beam with its two jaws.

FLUKA energy deposition studies showed that a mask is required to protect the superconducting coils of the separation dipole D1 from the particle showers generated in the TDI in a failure case. This mask, TCDD, is 1 m long and made of Cu. The TCDD avoids damage in any failure case and prevents quenches in most cases.

In order to complete the protection of the TDI, two auxiliary collimators are needed. They are called TCLI and guarantee coverage of MKI failures in case the phase advance between the MKI and TDI is not exactly 90° or if the TDI has to be further retracted because of unacceptable halo load. They thus enhance the overall flexibility of the system. Fig. 3 gives an overview of the elements in the injection region. One of the TCLIs, TCLIB, is close to the insertion quadrupole Q6 at $\Delta\mu = 360 - 20°$ from the TDI, the other one, TCLIA, is at the downstream end of the cold separation dipole D1 on the other side of the insertion at $\Delta\mu = 180 + 20°$. For TCLIB the TCS design is used. In the case of TCLIA, where both beams share a common beam pipe, a special half-jaw design will have to be applied similar to one of tertiary collimators (TCTs) at the D1 location.

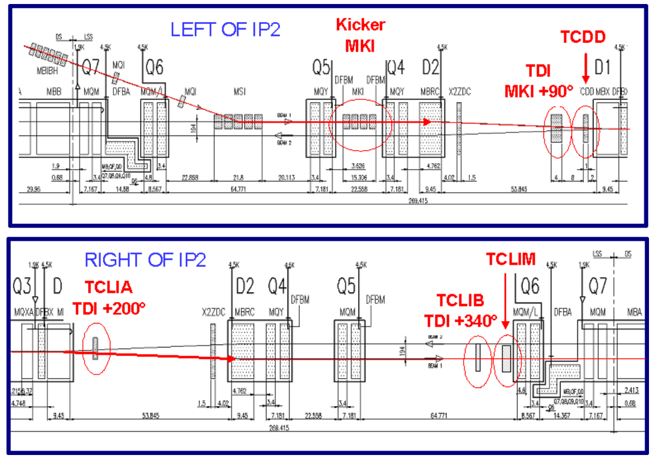

Figure 3: Overview of the injection region of IR2

SIMULATIONS OF THE OVERALL PROTECTION LEVEL

The performance of the protection systems was checked by means of extensive tracking simulations. The criterion for safe injection into the LHC was: losses on the aperture are below the 5% damage limit during the whole injection process.

MKI flash-over simulations

The protection level during an MKI flash-over is defined by the number of particles having an amplitude downstream of the chain of protection devices greater than the cold-bore aperture, as a function of the aperture of the system TDI-TCLI [5]. This number is obtained with particle tracking through the transfer line and the injection region in the LHC using MAD.

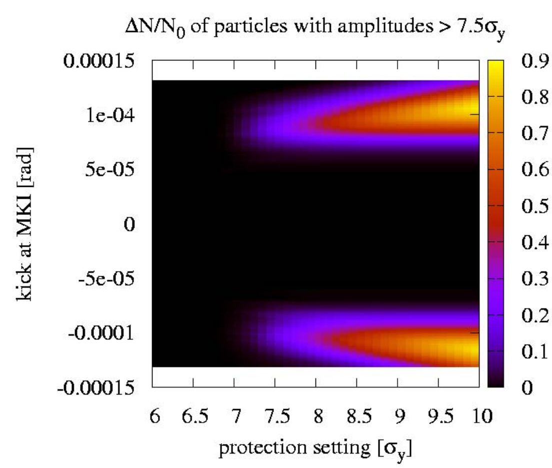

Figure 4: Number of particles getting into the LHC with amplitudes greater than 7.5 σ as a function of the protection setting of TDI and TCLI and of the MKI kick.

A realistic state of the transfer line was defined with a

Monte-Carlo for the random errors of power converter ripples, line drifts and SPS extraction error. These values were scaled to give a 95% confidence level for the injection error at the injection point in the LHC.

The MKI are travelling wave kicker magnets. Depending on the location of a flash-over in the magnet, the kick of a single MKI module can have any value in the range $\pm100\%$ of its nominal deflection. In the simulation a kick range from -0.15 to 0.15 mrad was scanned, with the maximum kick strengths of the range reaching about $10\,\sigma_y$ at the TDI. At the same time a scan of the settings of the TDI and TCLI from $6\,\sigma_y$ to $10\,\sigma_y$ was done. The number of particles above the cold-bore aperture compared to the damage level in the LHC at injection energy defines the required setting of the protection devices. Fig. 4 shows the results for such a scan with an available cold-bore aperture of $7.5\,\sigma$.

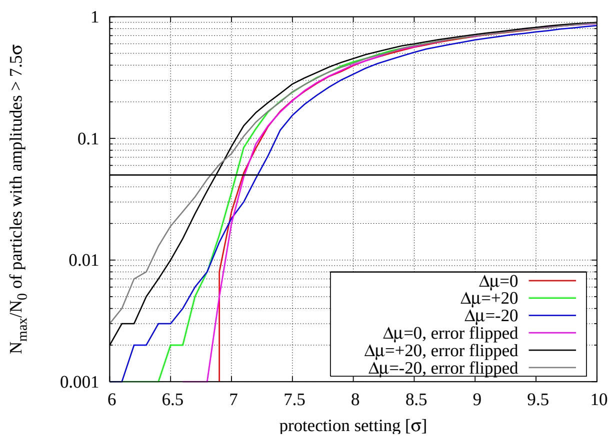

Figure 5: Maximum number of particles getting into the LHC with amplitudes greater than $7.5\,\sigma$ as a function of the protection setting.

Fig.5 summarizes the maximum number of particles into the LHC with amplitudes greater than $7.5\,\sigma$ as a function of the protection setting for different phase advances between MKI and TDI and different injection errors. The required protection setting of the system TDI-TCLI is $6.8\,\sigma$ to guarantee maximum 5% of the injected batch above $7.5\,\sigma$, the cold-bore aperture.

Monte-Carlo for single failure tracking

The overall protection level for the present layout of the protection systems was checked in a Monte-Carlo combined with a particle tracking. The whole injection process was simulated - connecting the SPS extraction region, the transfer line and the injection region in the LHC. The Monte-Carlo was used to sample different possible states of the extraction, the line and injection region. The tracking then was done with the MAD-X tracking routine for beam 2. Thus the particles were extracted from the SPS in LSS4, were transfered through the transfer line TI 8 and injected into the LHC in IR 8. The last element included in the tracking is Q6 downstream of TCLIB on the other side of the insertion.

Mismatch between SPS and transfer line and transfer line and LHC was randomly chosen between $\pm20\%$, anti-correlating vertical and horizontal plane. Random effects for power converter ripples, misalignments and tilts of accelerator equipment, beam jitter, etc. were included. For every seed the orbit of the transfer line was corrected to give a realistic trajectory. All present passive protection elements were taken into account; they were set to the required protection setting plus maximum tolerance. A full aperture model for the transfer line and the injection region was used.

Faults of all dipole families involved in the injection process were investigated. Each family was studied with 1000 different seeds and 1000 particles per run (since only %-level statistics are required to check for damage). For each run, loss patterns along the line and injection region were calculated and after the last element of the tracking the number of particles outside the LHC cold-bore aperture in phase-space was evaluated. Post-processing routines finally determined for each magnet family the maximum tolerable error in bending angle and the required reaction time for interlocking the power converter surveillance, see table 1. For the calculation of the required reaction time an exponential decay of the current is assumed as in the case of power converter faults (not applicable for kicker magnets). The output filter at the power converter is not taken into account. The obtained results hence do not give the real time of the power converter to reach the maximum tolerable current error, but the required reaction time for a safety system with safety margin.

Table 1: Results of Monte-Carlo for single failure tracking (PCS = normal power converter surveillance, FCDM = fast current decay monitoring).

Family	**Tolerable error** $[\Delta k/k_0]$	**required reaction time** [ms]	**covered by**	
			LHC	**TL**
MPLH	0.185	201.0	TCDI	PCS
MKE	0.125	-	TCDI	-
MSE	0.005	0.1	TCDI	-
MBHC	0.005	5.1	TCDI	PCS/ **FCDM**
MBHA	0.015	39.4	TCDI	PCS
MBI	0.003	2.7	TCDI	**FCDM**
MCIBH	0.630	389.0	TCDI	PCS
MBIAH	0.005	13.2	PCS	PCS
MBIBV	0.003	39.5	PCS	PCS
3MCIAV	0.225	124.0	PCS	TCDI
MSI	0.003	3.0	**FCDM**	n/a

Table 1 also states whether the LHC or the transfer line is protected and which main protection system covers the fault.

Discussion of the results – overall protection level

The results in table 1 show that the LHC is fully protected, provided an FCDM is implemented for the MSI (for FCDM see [6]). The requirements for this device resulting from the simulations are: *detect and react to a 0.3% current change in less than 2.5ms*.

The MBIs and the MBHCs in the transfer lines should also be equipped with an FCDM system. The required reaction time for an MBHC trip is 5.1 ms, which is at the limit for the normal power converter surveillance. For the MBIs it is only 2.7 ms.

MKE and MSE faults can still cause damage to the transfer line. These failures are not covered by the present protection system. However, an FCDM is recommended for the MSE to at least reduce the risk window (to fully cover MSE faults, a reaction time of 0.1ms is needed).

For all other failures of the studied dipole families both the transfer line and the LHC are protected. The TCDI system gives full protection for upstream failures for the LHC. Failures of magnet families at the end of the line, in the collimation section, are slow enough to be caught by the PCS.

Consequences of quadrupole failures have been studied analytically in [7] and are less severe. Grouped powering failures (e.g. general power cut) and combined failures (fault of machine protection system plus other failures) will be investigated in the future.

COMMISSIONING ASPECTS

The protection systems will play a limited role for early stage LHC commissioning. However, knowledge of injected beam intensity from the SPS is vital to avoid damage. The "safe beam" flag must be working from day one. Hence the SPS beam intensity monitoring, the link between the intensity monitor and LHC BIC and the LHC BIC must be fully functional for commissioning the LHC.

For intensities above the damage limit ($\sim$ 15 nominal bunches), the whole injection protection system is mandatory and must have been commissioned before.

A large part of the commissioning of the machine protection system can be done without beam. Examples are: LHC injection BIC plus injection conditions ("safe" beam,...) and data exchange, collimator movement, collimator interlocking, FCDM plus interlocking, PCS plus interlocking, logging, application software, software interlock system, etc.

For some tests beam is essential, e.g. for the SPS & LHC safe beam and beam presence conditions, which are based on BCT measurements. Another example is the TDI/TCLI/TCDI setting-up and jaw alignment. The full interlock system must be tested with beam to check for potential problems like EMC on instrumentation etc.

Commissioning of TCDI system

Preparative tests of the system like movement, software, instrumentation, calibration of potentiometers for position interlocking, etc. can be done without beam. This paragraph will deal with the beam based setting-up procedure for the passive injection protection devices.

The following steps are required for setting-up collimators:

1. finding the beam axis to center the jaws;
2. aligning the jaws with the beam envelope;
3. setting the jaws to the required gap (defining beam size).

The angular jaw alignment and beam size measurement for the transfer line collimators is based on a "transmission measurement". Two BCTs, one in the SPS and one downstream of the TCDIs, are needed to define transmission versus jaw position. As the TCDIs are at the end of the line, the second BCT has to be in the LHC. There are no BCTs in the LHC injection regions foreseen so far.

In order to align a jaw, it is fully closed and its ends are moved into the beam one after the other. The maximum of the curve - transmission versus angular misalignment - gives the optimum alignment with the beam, see Fig.6. Fig. 6 shows the result of a simulation of the measurement process with realistic parameters and tolerances. The attainable accuracy predicted by the simulation for the angular misalignment is $\pm 100\mu\mathrm{rad}$ R.M.S.

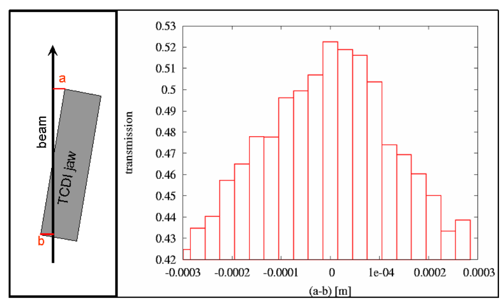

Figure 6: Simulation results for transmission versus angular misalignment. Realistic parameters and tolerances were taken into account.

The method of using a transmission measurement for aligning collimator jaws was tested experimentally during the TI 8 commissioning. The TCS collimator installed in TT40 for a robustness test was used for this purpose, which served as a proof-of-principle. A change of the angular misalignment had an obvious effect on the transmission. Those measurement results in Fig. 7, which are highlighted by the circle, show changes of the angular misalignment in steps of half a nominal σ.

The required beam intensity is maximum $\sim 10^{10}$ depending on the BCT resolution. The impact on the LHC for setting-up the TCDI would be "inject - TDI dump" in

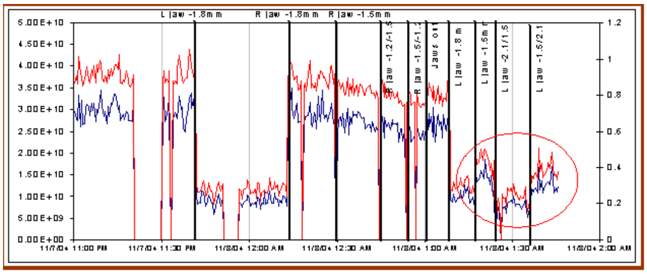

Figure 7: Experimental results of transmission measurement for different collimator jaw positions during the TI 8 commissioning.

case an additional BCT is available close to the MKI in the injection region. The alternative would be to operate in the "inject - dump"-mode or "inject plus several turns" and use a BCT in IR4.

Commissioning of TDI-TCLI system

The setting-up method of the TDI and the collimators TCLI is similar to the method developed for the TCDI with the difference that for some of the measurements circulating beam can be used.

The beam axis at the TDI and TCLI locations is measured with circulating pilot beam. The jaw alignment is done according to the TCDI method with "inject-dump" mode. The required intensities for the alignment again depend on the resolution of the BCT in IR4 (maximum $\sim 10^{10}$). The beam size measurement is finally done with circulating pilot (or maximum $\sim 10^{10}$) using a transmission measurement. Each jaw is moved through the beam and the transverse beam profile is reconstituted from the surviving beam intensity versus the jaw position.

CONCLUSION

With the nominal injected beam energy and intensity, machine protection is vital during the whole injection process. The "beam presence" criterion prevents many failures during the injection into the LHC.

The machine protection system will play a limited role during commissioning of the LHC and early LHC operation with low intensity beam, but must be correctly commissioned during the early stages. The "safe beam" flag must be fully operational from day one.

Comprehensive tracking simulations were used to define protection systems and to check the protection level. Results of these simulations show that the LHC is fully protected with the foreseen protection system, provided an FCDM is implemented for the MSI (specification: measure 0.3% current change in 2.5ms). At present the protection system cannot fully exclude transfer line damage. Simulations will be extended to grouped and combined failures.

Commissioning of the injection protection system is being prepared. Methods for setting up passive protection systems have already been worked out.

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